The Architecture of the CloudSat Mission

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This paper describes the CloudSat mission, a recent winner of the NASA Earth System Science Pathfinder mission competition. The paper provides a mission overview, describes two fundamental architectural decisions made to meet funding constraints, and concludes with lessons learned from the process.

Introduction

In April 1999, NASA announced a new Earth mission, which will take unique measurements of clouds and aerosols. This mission, developed under the leadership of Dr. Graeme Stephens of Colorado State University and selected in competition against some 25 other Earth science candidates, is called CloudSat.

CloudSat is being developed to investigate how clouds affect climate and to improve weather-prediction models. Clouds exert an enormous influence on our weather and climate. In addition to their key role in the atmospheric hydrological cycle, they dominate the energy budget of the planet through their influence on the Earth's solar and thermal radiation budgets. Clouds cool the Earth by reflecting sunlight back to space and warm the Earth by trapping thermal radiation emitted by the surface and the lower atmosphere. Cloud systems also modulate the pole-to-equator variations in solar insolation, which provide the fundamental drive for the global circulation. Because clouds have such a large effect on the Earth's radiation budget, even small changes in their abundance or distribution could alter the climate more than the anticipated changes in greenhouse gases, anthropogenic aerosols, or other factors associated with global change.

CloudSat will fill a gap in existing and planned observational capabilities. Current space systems only use passive sensors, which can only sense the bulk properties of clouds or probe the top-most cloud layer. They are unable to accurately measure the altitudes of cloud bases, retrieve ice and liquid water content, or probe the structure of multi-layer clouds. CloudSat will improve validation of weather-prediction models by directly measuring cloud characteristics that currently are predicted but not confirmed (e.g. vertical profiles of cloud tops, bases, ice and water). To improve the way that clouds are represented in climate models, CloudSat will provide the first quantitative, global description of vertical cloud radiative properties.

Perhaps more than any other factor, the architecture of this mission was driven by the cost constraints imposed by NASA Headquarters in this competition. The original estimate for the CloudSat mission was $185M, but $120M was the maximum amount the competition allowed. These cost constraints led to two significant architectural decisions: the extensive use of partners to provide funding for specific portions of the mission; and the use of formation flying with another spacecraft to make near-simultaneous measurements with both their payload and ours, thereby removing the need for CloudSat to carry an additional instrument.

Partnerships

The NASA Earth System Science Pathfinder (ESSP) Program is intended to accomplish high-quality, focused, Earth-science measurements by utilizing innovative, streamlined management and implementation approaches. The ESSP Program carries out science investigations by means of spaceborne observations with capped costs for the entire mission lifecycle. These costs are defined to include mission management; spacecraft and instrument definition and development; mission systems integration and test; launch services; on-orbit operations; mission science team support; algorithm development and data processing; data product archiving and distribution; and publication of results in refereed science journals. [Ref 1.]

ESSP missions must be designed and implemented within tight cost and schedule constraints, and contributions from sources other than NASA are encouraged. In point of fact, accomplishing the CloudSat science objectives within the ESSP funding constraints *required* the identification of partnerships with other funding agencies. The CloudSat proposal was accomplished by developing key partnerships with domestic and foreign agencies outside NASA. The success of these partnerships derived from the fact that they were based on key strengths of the contributing partner and were linked to benefit the partner beyond the immediate CloudSat mission goals.

Canadian Space Agency

Within the Canadian meteorological and remote sensing community, there exists a strong interest in the observation of clouds from space. Canada has been actively involved in many scientific studies relevant to the CloudSat mission, including similar studies with the European Space Agency. Canadian researchers will contribute to the validation of the CloudSat radar by operating ground-based radars in Canada and conducting appropriate in-situ aircraft observations. Additionally, Canadian researchers will participate in the scientific analysis of CloudSat data, including synergy with other space and ground measurements and the improvement of climate and weather-forecast models.

At the same time, active remote sensing of clouds requires technological developments that are relevant to Canadian industry. In terms of related technology, Canada has the unique capability for 94 GHz high power transmitter technology and a well-recognized capability in mm-wave RF technology. The Canadian Space Agency will provide the 94GHz Extended Interaction Klystron (EIK) and the RF front end for the CloudSat Mission.

U.S. Department of Energy

The fundamental goal of the U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Program is to understand and improve cloud and radiation processes in global climate models. This is also the underpinning goal of CloudSat and therefore CloudSat is a program that complements ARM and contributes to ARM by placing ARM-like observations in a global context. Likewise, the ARM program already supports the research that has lead to a maturing of the techniques and algorithms to be used by the CloudSat mission. The ARM Program will contribute the core observations for CloudSat algorithm development and validation from its continuous and routine data collection in the Southern Great Plains, the North Slope of Alaska and the tropical West Pacific. These sites are fully instrumented, including ground-based radar and lidar observations and regular aircraft deployments in Intensive Observational Periods.

U.S. Air Force

CloudSat observations have great potential importance to defense operations. CloudSat will demonstrate the value of cloud radar observations to support operational weather analysis and forecasting. Once demonstrated, cloud radar technologies could be adopted for sustained operational use by the National Polar-Orbiting Operational Environmental Satellite System (NPOESS). The charter of the Air Force Space Test Program (STP) is to provide spaceflight for a ranked list of DoD experiments, reviewed by the DoD Space Experiments Review Board (SERB). The CloudSat mission was reviewed by the SERB and was included in its FY98 and FY99 ranked list. STP and JPL joined in a study to determine the level and type of support for the mission. As a result of this study, the STP program offered to commit funds to provide the mission operations for CloudSat. STP will provide the ground data system, including staff and antenna support, through the mission lifetime of 2 years.

Picasso-CENA Mission

A combination of lidar with the 94 GHz CloudSat radar provides significant improvements in our abilities to assess cloud radiative forcing and feedback and was a key element of the CloudSat mission architecture. Within the NASA funding constraints of the ESSP-2 program, it is not possible to carry a cloud radar and a lidar on the same spacecraft. The NASA Picasso-CENA mission, planned to launch in the same timeframe as CloudSat

(March 2003) carries a lidar and flies in loose formation with the Earth Observing System PM satellite (EOS-PM). The addition of CloudSat cloud radar data is accomplished by formation flying in tight formation with Picasso-CENA.

The Picasso-CENA team participated with the CloudSat team in a preliminary technical analysis of the feasibility of dual launch and formation flying with CloudSat. There are significant cost and technical benefits to a combined Delta launch over two, individual Taurus launches, and NASA has agreed to co-manifest the two spacecraft. Additionally, this approach enhances the scientific objectives of Picasso-CENA (including joint studies planned between Picasso-CENA and EOS-PM) and the scientific objectives of the CloudSat mission itself.

Formation Flying

Formation flying is a navigational strategy where the separation and relative motions of two spacecraft are controlled to preserve a pre-specified geometry. As the funding constraints of ESSP made carrying both a radar and lidar impossible, the CloudSat team elected to carry a radar and employ this technique to take advantage of measurements being made from the lidar instrument of the Picasso-CENA mission.

For scientific reasons, it is desirable that the average along-track separation between CloudSat and Picasso-CENA be made as small as practical, so as to be near-simultaneous. Currently the science team is requiring a mean separation of 224 km or equivalently 30 seconds between measurements.

The primary navigational requirement is to formation fly with Picasso-CENA at a specified separation and maintain, as closely as possible, the same groundtracks. For the Picasso-CENA /CloudSat mission scenario, Picasso-CENA is the "master" spacecraft and CloudSat is the "slave" or burdened spacecraft which must react to Picasso-CENA's motion and maneuvers. Therefore, CloudSat will be responsible for implementing the spacecraft maneuvers required to maintain the formation.

The second part of the navigation requirement for formation flying relates to cross-track control, which is equivalent to groundtrack control. Again for scientific reasons it is desirable to maximize the amount of overlapping coverage by the radar and lidar footprints. This ultimately must be traded with the frequency of formation flying maneuvers necessary to maintain tight control on the cross-track motion. Based on preliminary analyses, CloudSat can control the cross-track variations in groundtracks to differ by no more than +/- 450 meters. This translates into the radar and lidar footprints overlapping approximately 62% of the time (assuming a Gaussian distribution for the Picasso-CENA pointing control error).

To first order the cross-track motion of CloudSat relative to the ground track of Picasso-CENA is a parabolic curve with CloudSat moving from west to east. This motion is related to differential drag forces acting on each spacecraft and is coupled with CloudSat's motion along-track on the circulation orbit. Eventually the cross-track motion slows, stops, and reverses direction, just as it is shown to slow and reverse its along-track motion on the circulation orbit. In time CloudSat will return to its western boundary relative to Picasso-CENA and must then perform a propulsive maneuver to meet its navigation requirement and start the cyclic process over again.

At the beginning of the mission when drag effects will be most pronounced, the time around the circulation orbit and between maneuvers is only 5.4 days. This calculation is based on using conservative assumptions for the atmospheric drag environment; as the mission progresses the solar maximum subsides and the drag environment should become less severe. The propulsive maneuver necessary to restore the spacecraft onto the beginning of the circulation orbit again is approximately 8 cm/sec. Thus, over the mission life no more than 17 m/sec in delta-velocity change will be required for CloudSat to perform formation flying with Picasso-CENA.

Mission Overview

Payload

To accomplish the scientific objectives of this mission, CloudSat will carry two instruments, the Cloud Profiling Radar (CPR) and the Profiling A-band Spectrometer/ Visible Imager (PABSI), in addition to sharing observations with the lidar flown on Picasso-CENA.

The CPR is a 94-GHz nadir-looking radar, which measures the power backscattered by clouds as a function of distance from the radar. The CPR will be developed jointly by NASA/JPL and the Canadian Space Agency (CSA), as described previously.

PABSI consists of two instruments packaged together: a high-resolution spectrometer and a 2-channel imager (camera). The objective of the PABSI instrument is to resolve the O_2 A-band spectrum in the 12950 - 13130 cm-1 (761.61 nm to 772.20 nm) range; and to acquire narrow-band images at 747.5 and 761.5 nm to provide the spatial context for the PABSI spectrometer and the CPR. Both the imager and spectrometer are sensitive to reflected sunlight and thus only generate science data on the dayside of the Earth.

Most components of the CloudSat payload are mature, but one component of the CPR, the 94 GHz Extended Interaction Klystron (EIK) transmitter, requires space-qualification. The family of EIKs, developed by Communications and Power Industries (CPI) Inc., of Toronto, Canada, has been used extensively in existing ground-based and airborne 94 GHz cloud radars. No fundamental development of new technology is required, but a re-packaging for the vibration environment of launch and the thermal environment of space is required.

Mission Design

The CloudSat mission design is based on the CloudSat spacecraft flying in formation with the Picasso-CENA spacecraft. The precision of the formation maintenance is such that near-simultaneous, congruent measurements will be made of the same cloud formations as each spacecraft moves along essentially the same groundtrack. This means that many of the mission design options and trades normally available to the Science Team and/or the Systems Engineering discipline are precluded because they have already been decided by Picasso-CENA. For example, the orbit has already been determined by the Picasso-CENA mission design.

For planning and budgeting purposes, the launch date agreed to by the CloudSat and Picasso-CENA Projects is March 2003. This launch date is based on the availability of the Delta launch complex at VAFB and the projected use of that pad per the launch manifest.

The nominal mission duration for the Picasso-CENA mission is three years. The nominal duration for CloudSat is 25 months. This allows CloudSat to perform two years of nominal operations, starting after one month of on-orbit checkout. During this one-month period, CloudSat will be maneuvered into formation with Picasso-CENA. This same month will also be used to perform spacecraft checkout and calibration and instrument calibrations prior to beginning the nominal operational mission.

Table 1. Orbit Description and Parameters

Orbit equatorial altitude (ref.)	705 km
Semi-major axis	7083.14 km
Eccentricity	≈0.0012
Inclination	98.08 deg
Initial ascending node position	31.06 deg or 14:04 hours wrt to sol meridian
Final ascending node position	20.56 deg or 13:22 hours wrt to sol meridian
Ascending node precession rate	0.9701 deg/day
Argument of perigee position	≈90 deg
Period	98.88 min
Perigee altitude	717.47 km
Apogee altitude	734.47 km
Min. altitude	705 km
Max altitude	734.47 km
Altitude variation	29.77 km (+/- 8 km for EOS FF)
Along-track orbit speed	7.052 km/sec
Groundtrack speed	6.755 km/sec
Orbit angular rate	0.0607 deg/sec
Shadow time variations	32.6 – 35.2 min
Beta-angle variations	58.4 – 83.3 deg

The CloudSat operational orbit is very nearly the same as the operational orbit for Picasso-CENA. It is approximately circular at an altitude of 705 km. The inclination is very nearly sun-synchronous at 98.08 deg. The inclination is not exactly sun-synchronous so as to cause the orbit plane to precess slowly with respect to the EOS-PM orbit plane. This slow precession, coupled with the careful selection of the initial ascending node position, gives both CloudSat and Picasso-CENA the opportunity to make coincident radar/lidar measurements with the MODIS instrument on EOS-PM. MODIS is the Moderate-Resolution Imaging Spectroradiometer with a field of view extending 110 deg as seen from the EOS-PM spacecraft. This corresponds to a swath width of 2330 km centered on the nadir groundtrack or equivalently a ±10-deg central angle measured on the Earth's surface. Thus coincident observations from Picasso-CENA and CloudSat will be possible at varying atmospheric look angles from MODIS so long as the nadir looking Picasso-CENA and CloudSat are over the MODIS measurement swath. The choice of the initial nodal position relative to EOS-PM's node guarantees this condition throughout the mission. The designated orbit inclination causes CloudSat to precess westward at 0.016 degrees per day with respect to EOS-PM's sun-synchronous orbit plane.

Spacecraft

The spacecraft is a version of the Ball Aerospace RS-2000 commercial line, requiring only small changes to accommodate the CloudSat payload. CloudSat will be the 5th RS2000 spacecraft, preceded by QuikSCAT (Figure 1), ICESat, and the two QuikBird spacecraft. The RS2000 has extensive heritage from ERBS (flying since 1984), RadarSat (flying since 1995) and GeoSat Follow-On (launched early 1998).

The CloudSat RS2000 bus will have two significant modifications from its baseline design: a shortened structure, and the use of SGLS transponders.

The shortened structure is a result of the CloudSat/ Picasso-CENA dual launch. CloudSat and Picasso-CENA will be launched together on Delta 7420-10 using a the Dual Payload Attachment Fairing (DPAF) (Figure 2.) The constraints of the DPAF require shortening of the CloudSat side panel height by 61 cm. However, as the RS2000 was originally designed with an internal payload section, and the CloudSat instruments are both external, removing this interior volume can satisfy the reduced height constraint without a major spacecraft redesign.

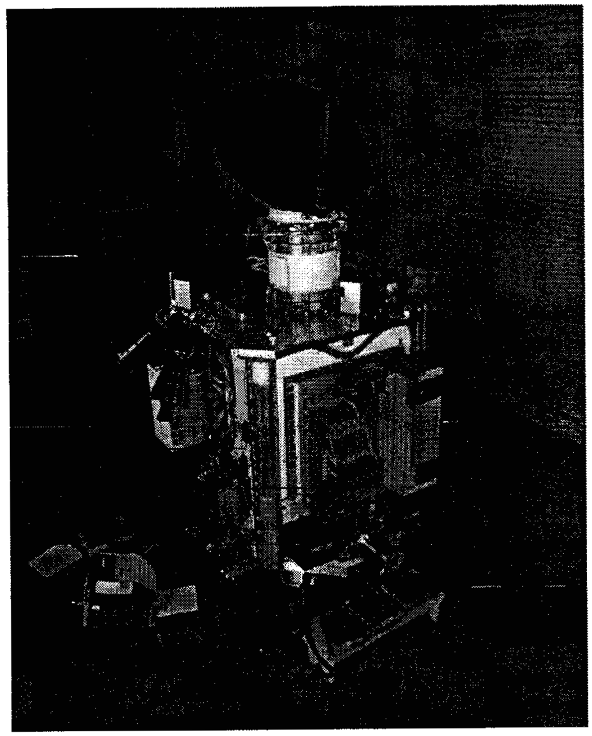

Figure 1. The RS2000 bus, shown in its QuikSCAT configuration.

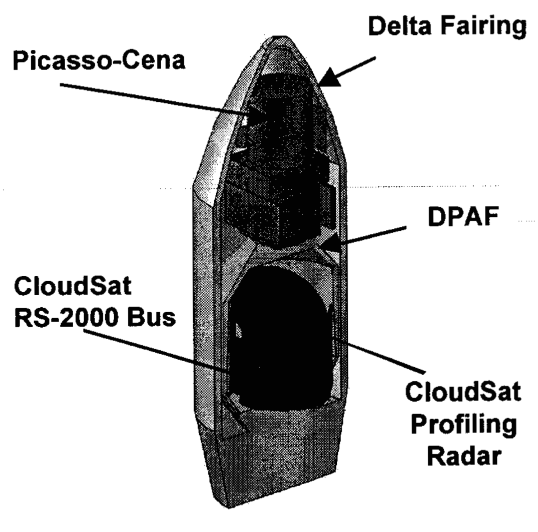

Figure 2. CloudSat/Picasso-CENA Dual Launch Configuration

Using the US Air Force for mission operations requires changing to SGLS-compatible transponders. The spacecraft RF uplink/downlink uses redundant SGLS transponders for data transmission and reception. The uplink command data rate of 2000 bps has a worst-case link margin of 13 dB. Science data is downlinked on a carrier signal at a rate of 5 Mbps, with a worst-case margin of 6 dB. A nadir pointing patch antenna is used for science data transmission. Stored engineering data is downlinked at a rate of 256 kbps on a second carrier signal, with a margin of 6 dB. Real-time data is downlinked on a subcarrier with the stored engineering data at 16kbps with a worst-case margin of 5.4 dB. A multiple-patch antenna configuration provides spherical coverage for telemetry, command transmission and reception.

A summary of the characteristics of the CloudSat spacecraft is given in Table 2.

Table 2. Spacecraft Characteristics

Parameter	Characteristic
Design Life	>5 years
Launch Vehicle	Delta 7420-10
Approximate Size	1.9 x 1.9 x 2 m
Mass (wet)	677 kg
Redundancy Approach	Fully Redundant Bus. Ps = >0.95
Control System	3-axis stabilized, zero net momentum, stellar-inertial
Navigation	GPS
Available Power	1375 W EOL
Solar Array Size, Type	6.9 sq.-m, single-axis articulation and s/c yaw maneuvers, dual-junction Ga/As cells
Onboard Data Storage	32 Gbits
Comm. Approach	SGLS, 5 Mbps downlink, 2 kbps uplink
Thermal Control	Primarily passive with some survival heater control

The payload configuration maximizes the size of the CPR antenna while still satisfying the DPAF envelope. The CPR is mounted to an upper deck using semi-kinematic mounts that allows it to be co-aligned with the PABSI. All other spacecraft components and the PABSI are mounted to the exterior surfaces of the shear panels. An exploded view of the spacecraft showing the various components is shown in Figure 3.

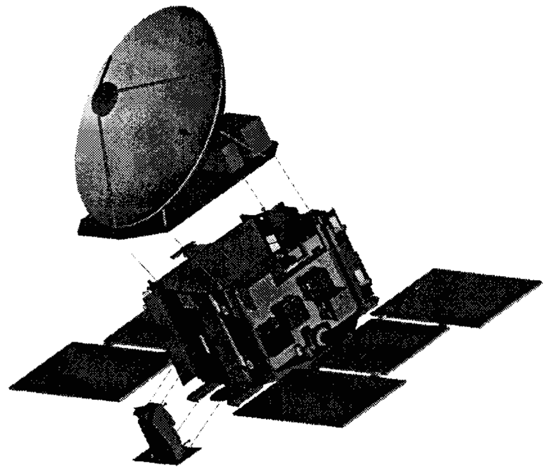

Figure 3. The RS2000 Bus (center), the CPR (above), and the PABSI (below).

Ground System and Mission Operations

The CloudSat ground system uses the existing facilities and personnel of university and military partners. The USAF Research-Development-Test-&-Evaluation Support Complex (RSC) facility at Kirtland Air Force Base will provide flight operations, including mission planning, command generation, telemetry monitoring, spacecraft engineering, level-0 data processing. The Air Force Satellite Control Network (AFSCN) will be used by the RSC for all CloudSat ground antenna support.

Colorado State University's CIRA (Cooperative Institute for Research in the Atmosphere) facility will provide science data processing, which includes levels 1-N data processing, distribution, and data archiving.

The Jet Propulsion Laboratory will provide mission management and the science team interface during operations. A block diagram of the GDS showing the end-to-end concept for operations data flow is shown in Fig. 4.

CloudSat's data acquisition strategy is simple and does not vary during the mission. The CPR collects data continuously, while PABSI collects data when the ground beneath it is illuminated by the sun. This collection pattern is retained throughout the entire mission. CloudSat does not need frequent ground contacts from a control point-of-view, as it has no short data latency requirements or adaptive commanding requirements.

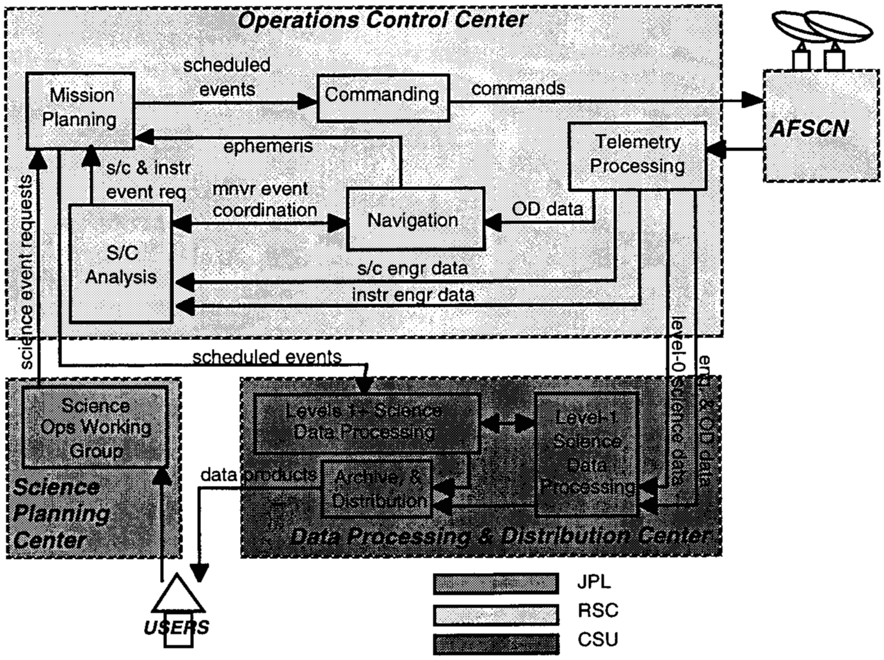

Figure 4. The CloudSat Ground System

The data return strategy was designed to be compatible with a 5 Mbps S-band downlink, so that any of the eight existing AFSCN antenna sites (Figure 5) can be used to support CloudSat as they are configured today. In a typical day, CloudSat is in view of the AFSCN for more than 4.5 hours, of which only 28 minutes are needed to return an entire day's worth of data, a mere 10% usage requirement. CloudSat will collect 6.7 Gbits of data per day, but carries 32 Gbits of onboard storage, enough for outages lasting several days without losing science data.

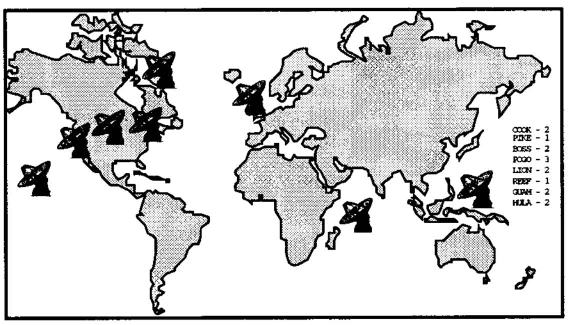

Figure 5. CloudSat is compatible with all the AFSCN global assets, providing maximum flexibility for tracking support.

The operational scenario begins at JPL, where a conflict-free set of high-level science plans will be produced. At regular intervals, these plans will be delivered to the RSC, where they will be used to develop command loads. Real-time operations can be performed 24 hours a day, 7 days a week. The mission control team will consist of mission planners, orbit analysts, and contact specialists. Mission planning is performed in mission dedicated areas, complete with mission documentation and mission specific computers and software. The RSC will run 4 contacts per day using the AFSCN. Once the science data returned and level-0 processed by RSC personnel, it will be shipped via tape to CIRA for data processing.

CIRA will process and archive data to produce CloudSat mission science data products for delivery to the NASA DAAC. In addition, CIRA will collect and archive supportive data such as geostationary satellite imagery, synoptic surface observations, upper air observations, and other data required by the Science Team. Because these data are normally available at CIRA, this is provided at no extra cost to CloudSat. The supportive data will be used both for input to Science Team applications and for the quality control of the CloudSat Level 0 data and subsequent physical interpretation of the

CloudSat science data products. The ancillary data will be archived by the CIRA along with CloudSat Level 0 data using the EOS-DIS HDF format for transfer to the appropriate NASA DAAC.

Lessons Learned

Form Partnerships Early

The development of each partnership requires resources and a great deal of time to accomplish. Multiple interactions with each potential agency are required. Based on experience with CloudSat, our recommendation is to begin this process at least one year ahead of the anticipated proposal date. Some agencies have internal review cycles on an annual basis, and these reviews may be needed for approval of commitments and allocation of resources.

Build a Broad Support Base

The concept for the CloudSat mission grew from the expressed needs of the international scientific community, including the weather forecasting centers and the climate research community. The World Climate Research Programme's (WCRP) Global Energy and Water Cycle Experiment (GEWEX) program hosted the first international workshops on cloud radar and communicated to the world's space agencies of the need for spaceborne cloud radar measurements. In a process which lasted over six years, a broad base of support and awareness grew.

Thus, before the CloudSat proposal was submitted to NASA, NASA was aware of the need for the mission and anticipated the proposal submission. By the time that CloudSat was submitted as an ESSP proposal, there was no doubt that this was a high-priority scientific mission. Letters of endorsement for the mission came from the military sector, the weather-prediction centers and the climate research community. Even so, the ESSP competition was intense, with several high-value science missions on the table. Nonetheless, CloudSat was known and strongly supported, a factor which contributed to the outstanding scientific score during the ESSP evaluation process.

Generating this type of support can take years to accomplish. Broad support also increases chances of success in partnering with other agencies.

Buy the More Capable Spacecraft

As part of the proposal process, the CloudSat team put out a request of proposals (RPF), which was answered by five aerospace companies. These companies submitted production spacecraft designs, with the objective of being selected as a partner for the proposal. As part of this RFP, the CloudSat team listed both minimum spacecraft capability requirements and a maximum allowable cost. Of the five vendors which answered this RFP, two clearly met the guidelines. It was at this point that the CloudSat team was faced with a very difficult architectural decision. One vendor elected to provide margin in the cost (meaning a lower price than the cap we set) while meeting the spacecraft requirements. The second vendor elected just the opposite: provide margin in the spacecraft design (meaning extra capabilities) while meeting the maximum allowable cost.

The cost-constrained nature of this process made the cost savings offered by the first vendor quite attractive. However, after a great deal of agonizing, the CloudSat team elected to spend the whole of its budgeted amount for the more capable spacecraft. As a general rule, it is our opinion that a project will benefit in the long run by adding margin in their spacecraft design. In recent months, as design details beyond the scope of a proposal effort came into focus, this decision has been proven to be the correct one for CloudSat.

Conclusions

The CloudSat mission will launch in March 2003. CloudSat was selected in a large part because of creative work done to control mission costs. The original, projected cost of this mission was $185M. The architectural decisions described in this paper reduced NASA's cost of CloudSat to $111M, well below the $120M cost cap. A summary of these savings is given in Table 3.

Table 3. Summary of cost savings, resulting from architectural decisions.

	Cost reduction to NASA
Use of formation flying to provide LIDAR measurements	$30M
Net launch vehicle savings, going from cost of one Taurus launch vehicle a shared launch with a Delta 7420-10 with DPAF	$20M
Partner Contributions (USAF contribution of operations, DOE contribution of validation, CSA contribution of radar components)	$24M
TOTAL	$74M

The CloudSat mission builds on considerable design heritage and design maturity. This is necessary given the quick schedule to launch, a guideline of the ESSP program, and the need to stay within the ESSP cost cap.

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[1] NASA Earth System Science Pathfinder Announcement of Opportunity – 2, AO-98-OES-01, April 1998.